

Accelerators, Beamlines, Experimental Apparatus, and Experimental Techniques

Accelerators

A new method to understand momentum aperture in particle accelerators

Steier, C., L. Nadolski, D. Robin, Y. Wu, W. Decking, J. Laskar

Coherent far IR bursts measured at BL 1.4.2

Martin, M.C., J. Byrd, F. Sannibale, W.R. McKinney

Giant terahertz power levels from relativistic electrons

Carr, G.L., M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil, G.P. Williams

A New Method to Understand the Momentum Aperture in Particle Accelerators

C. Steier¹, L. Nadolski¹, D. Robin¹, Y. Wu¹, W. Decking², J. Laskar³

¹Lawrence Berkeley National Laboratory, USA

²DESY, Germany

³Astronomie et Systèmes Dynamiques, IMC-CNRS, France

Storage rings are used for a variety of science and technology applications - for example as synchrotron light sources or as colliders for particle physics. In these storage rings, bunched particle beams circulate for many hours. The motion of a particle can be described in terms of transverse (betatron) and longitudinal (synchrotron) motions with respect to the reference particle. Some particles may be lost due to various aperture limitations. The momentum aperture is defined as the maximum momentum deviation that a particle can have without becoming unstable and being lost. The momentum aperture is determined by the complex 6-dimensional dynamics of the particle. Because of the complexity of the dynamics, up to now there have been unexplained discrepancies between the predicted and measured momentum aperture.

In many cases the momentum aperture is the dominating factor determining the beam lifetime. Long lifetimes are desirable to users of synchrotron light sources since they increase the integrated photon flux, reduce the frequency of refills, and improve the stability by reducing thermal effects. In those storage rings where the dominant lifetime process is Touschek scattering, the lifetime has a stronger than quadratic dependence on the momentum aperture. The Touschek lifetime at the ALS of 9 hours is much shorter than the vacuum lifetime of 60 hours, so the ALS would benefit greatly from a larger momentum aperture. Therefore it is important to understand what limits the momentum aperture. This knowledge will help improve the performance of existing light sources as well as to help predict and optimize the performance of future storage rings.

The particle dynamics [1,2] and momentum aperture [3] have been extensively studied at the ALS. A schematic of the process leading to particle loss after Touschek scattering is shown in Fig. 1. Due to Touschek scattering a particle receives a certain energy offset (here 3%). If the scattering happens at a position of the ring with dispersion, this energy change will also induce a transverse oscillation (red circle). Due to the tunes shift with energy (chromaticities) and tunes shift with betatron amplitude, the betatron tunes (i.e. the number of transverse oscillations in one revolution) of the particle change as well (right part of the figure). Afterwards, the particle undergoes energy oscillations and slowly damps back to the nominal orbit (green circle). Because of the chromaticities and the tunes shift with amplitude, the tunes get modulated during this process and eventually the particle might encounter a resonance or an area of high diffusion and might be lost.

Tracking particle trajectories using a realistic representation of the ALS lattice confirmed that the model of particle loss mentioned in the previous paragraph is correct. Fig. 2 shows the trajectory of a particle tracked for 10,000 turns including the effects of synchrotron radiation. On the left side, you can see the horizontal and vertical position of the particle. On the right side the betatron tunes are shown (calculated every 300 turns). At certain times (marked (a) to (c) in Fig. 2) when the tunes cross resonances, growth of the oscillation amplitude is observed. On some of those occasions, the particle got very close to the vacuum chamber (± 4 mm). Particles with slightly different initial conditions can be lost.

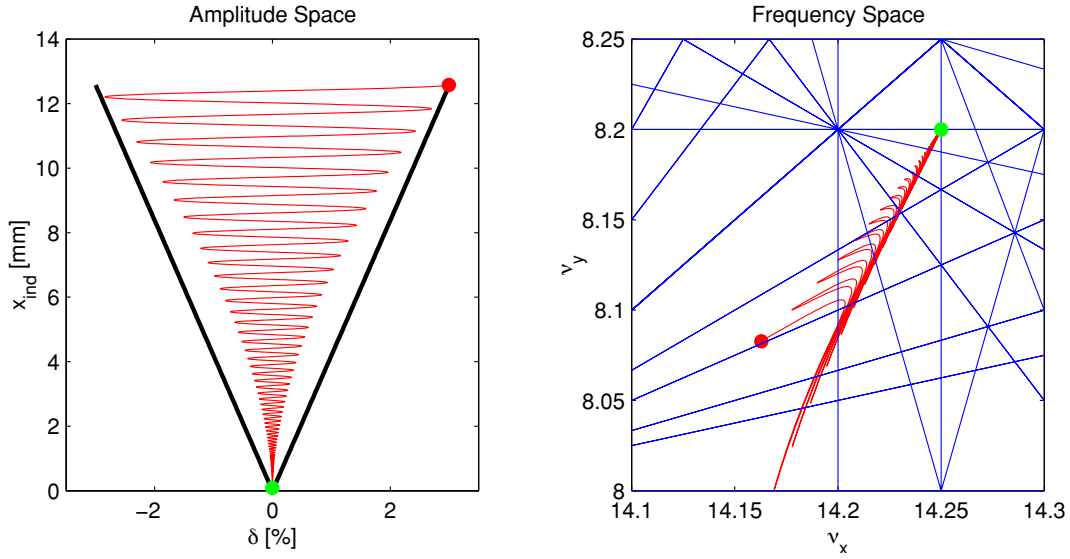


Fig 1: Left: Schematic of particle behavior after Touschek scattering. Initial particle position after being scattered (red circle) then oscillating in energy and amplitude (solid line) and damping back down to the nominal orbit (green circle). Right: particle motion tracked in the tune space (ν_x , ν_y), showing the effect of tune shift with betatron amplitude and tune shift with energy. Resonances up to the fifth order are shown.

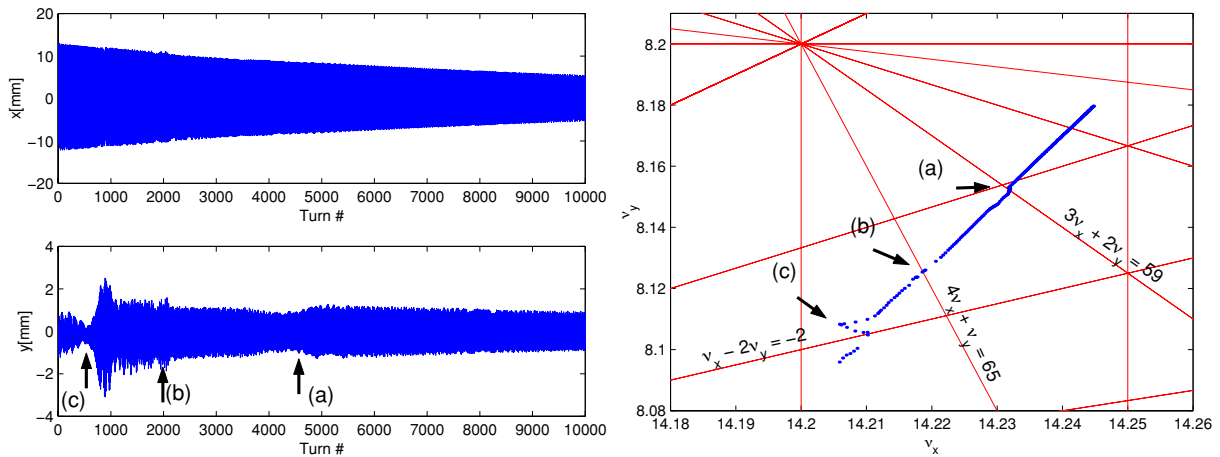


Fig 2: Tracking of a particle with synchrotron oscillations and radiation damping (in tune and configuration space). When the trajectory crosses a region with high diffusion (see labels (a) to (c)), the vertical oscillation amplitude increases and at (c) the particle gets very close to the vacuum chamber aperture of 4 mm.

The main tools to understand the momentum aperture are two classes of measurements. Both methods clearly show that the major limitation to the momentum aperture is the transverse beam dynamics, causing Touschek scattered particles to eventually reach large vertical amplitudes where they are lost on the vacuum chamber (compare ALS activity report 2000). Analysis of the measurement data using Frequency Map Analysis allows us to understand the details of the beam loss - identifying those resonances that limit the momentum aperture. One example using the nominal ALS lattice is shown in Fig. 3. The left plot shows relative beamloss in the configuration space formed by energy offset and horizontal oscillation amplitude. One can clearly see the complicated structure of the boundary of the stable area. The right plot shows the

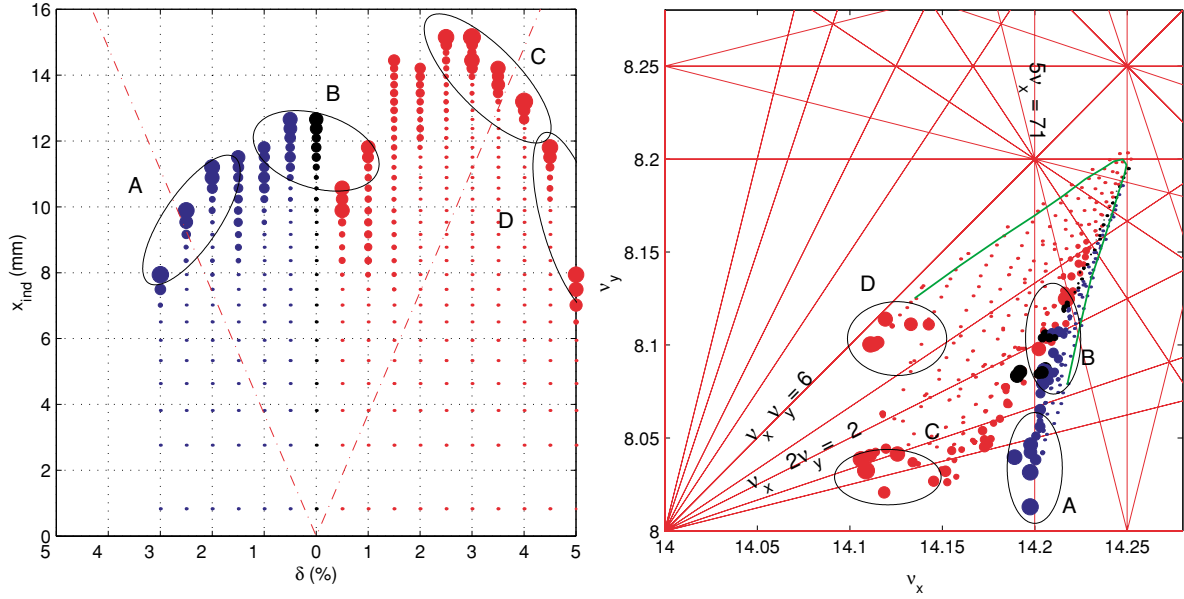


Fig 3: Measured momentum aperture in tune (right) and in configuration space (left) for a chromaticity of ($\xi_x=0.4$, $\xi_y=1.4$). Point size indicates relative beam loss and labels point out specific resonance areas responsible for these losses. Resonances up to the fifth order are shown in the tune space.

same data in frequency space. By recording the tunes of the particles after they have been kicked, one can clearly identify which resonance areas are causing the beam loss. By using this information, one can now understand (compare areas A-D in the plots) what caused particular loss regions. The knowledge gained as a result of these measurements allows us to adjust the machine parameters to improve the lifetime. For two-bunch operation a better choice of the linear chromaticities resulted in a 25% increase in the lifetime.

References:

- [1] D. Robin, J. Safranek, and W. Decking, Realizing the Benefits of restored Periodicity in the Advanced Light Source, Phys. Rev. ST Accel. Beams 2, 044001 (1999).
- [2] D. Robin, C. Steier, J. Laskar, and L. Nadolski, Global Dynamics of the Advanced Light Source Revealed through Experimental Frequency Map Analysis, Phys. Rev. Lett., 85, 3, 558 (2000).
- [3] C. Steier, D. Robin, L. Nadolski, W. Decking, Y. Wu, and J. Laskar, Measuring and Optimizing the Momentum Aperture in a Particle Accelerator, accepted to Phys. Rev. E

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy, under Contract No. DE-AC03-76F00098, by Centre National de la Recherche Scientifique (France) and by Bundesministerium für Bildung und Forschung (Germany).

Principal investigator: Christoph Steier, Lawrence Berkeley National Laboratory. Email: CSteier@lbl.gov.
Telephone: 510-495-2992.

Coherent Far IR Bursts Measured at BL 1.4.2

Michael C. Martin, John Byrd, Fernando Sannibale, and Wayne R. McKinney
Advanced Light Source, Lawrence Berkeley National Laboratory
University of California, Berkeley, California 94720, USA

INTRODUCTION

We have performed the first measurements at the ALS of coherent far-IR bursts coming from instabilities within a high-current single electron bunch.

The 2-bunch mode operations of the ALS afforded us the opportunity to use the machine while it was tuned for high currents in individual electron bunches. We have used a number of accelerator physics shifts to make measurements with well-controlled setups as well as additional measurements during normal 2-bunch operations. Recent investigations at other light sources [1-6] have observed far-IR bursting at high bunch currents. We want to investigate these bursts more carefully towards the goal of understanding how to make use of high-intensity coherent far-IR synchrotron light as a new source of far-IR that is many orders of magnitude brighter than the best presently available sources.

TIME DOMAIN MEASUREMENTS

As an initial investigation into coherent far-infrared synchrotron radiation we placed a liquid He cooled Silicon Bolometer with integrated pre-amplifiers just outside a 20 mm diameter diamond window mounted in the 'switchyard' at Beamline 1.4. A single extra mirror was inserted in the switchyard to direct the collimated beam through this window into the bolometer without disturbing the alignment of the IR beamlines. A digitizing oscilloscope recorded the output of the detector. We observed large intensity bursts when the single bunch current was very high. Fig. 1 shows time traces of the bolometer output voltage for three different beam currents in single bunch operation. Although the bursts seemed to be quasi-random, at certain currents the bursts occurred within a periodic envelope, as evidenced by the middle trace in Fig. 1. The rise and fall times of the bursts were detector limited, therefore the damping mechanism may not be inferred immediately. The single bunch current threshold for the onset of

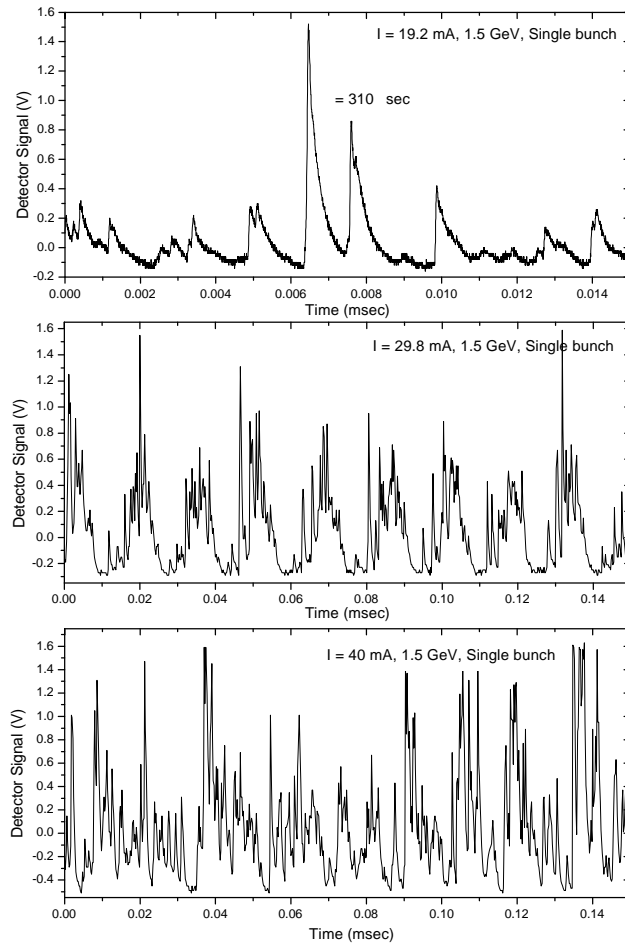


Figure 1. Far-IR detector signal vs time for three different beam currents. Note the expanded time scale for the top panel.

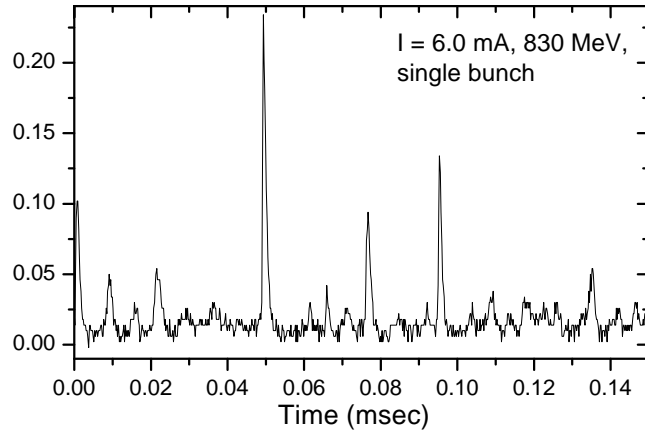


Figure 2. Bursting observed at 830 MeV which shows a quite different time envelope.

the RF power from 120 to 1.5 KW.

A measurement of the bursting at 830 MeV electron energy at 6 mA single bunch current showed distinctly different time behavior as shown in Fig. 2.

SPECTRAL MEASUREMENTS

By using a combination of filters with the above setup we determined the spectral content of the bursts was below 100 cm^{-1} (wavelengths longer than 100 microns). To make this more quantitative, we used the Bruker 66v/S FTIR spectrometer on BL 1.4.2 to measure the bursts that occur at the very top of the fill during regular 2-bunch mode operations. By quickly averaging 100 interferograms over 50 seconds we integrated long enough to demonstrate the average spectral content of the bursts. Shown in Fig. 3 is the measured intensity of the bursts as a function of wavelength, ratioed to the incoherent synchrotron signal measured at low beam current. The bursts are peaked at $\sim 27 \text{ cm}^{-1}$. This indicates a microbunching within the electron bunch having a period on the order of 400 microns (or approximately 30 times smaller than the normal ALS bunch length). The bursting was clearly dependent on the beam energy, with higher intensity at 1.5 GeV. This is to be expected, as the bunch length is proportional to $E^{3/2}$, implying higher peak currents at 1.5 GeV than 1.9 GeV, and therefore a greater tendency for instabilities and hence microbunching. Overall, the burst intensity dropped with decreasing beam current, with the spectral content remaining essentially unchanged.

We are continuing these measurements to gain a greater understanding into coherent synchrotron emission both

bursts is approximately 7 mA at 1.5 GeV. The transition to bunching of the bursts within a super period occurs at about 27 mA at 1.5 GeV.

Since the bursts seem to be related to high peak currents within a bunch, reducing the RF power will lengthen the bunch and therefore cause the bursts to stop. At 14 mA and 1.9 GeV, the bursts go away by reducing the RF power from 120 to 90 KW; returning to 120 KW causes the bursts to reappear. At 1.5 GeV and 14 mA, the bursts can be stopped by dropping

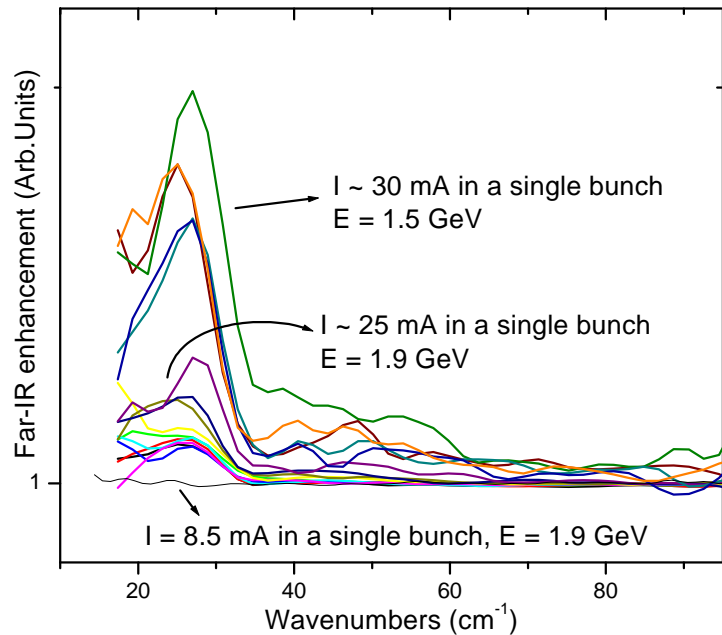


Figure 3. Spectrum of coherent far-IR bursts measured at BL1.4.2 as the current was decaying.

from instabilities (as measured here) and hopefully in a stable manner. In the near future, we will make additional measurements using femtosecond sliced electron bunches (in collaboration with the femtosecond x-ray team at LBNL) which will allow a clean study of coherent emission from a well known transient short bunch. Because this will be a laser pumped measurement with synchronized optical detection, electron beam instabilities and oscillations will not be a factor. We have also collaborated with researchers at Brookhaven National Laboratory and Thomas Jefferson National Laboratory to measure the coherent far-IR emitted from a bend magnet in their energy-recovery linear accelerator based infrared free electron laser [7] (reported in a separate compendium abstract).

REFERENCES

1. H. Tamada and H. Tsutsui, *Nuclear Instr. & Meth.* **A331**, 566 (1993).
2. A. Andersson, M. S. Johnson and B. Nelander, *Optical Engineering*, **39**, 3099 (2000)
3. U. Arp, G.T. Fraser, A.R. Hight Walker, T.B. Lucatorto, K.K. Lehmann, K. Harkay, N. Sereno and K.-J. Kim, *Phys. Rev. Special Topics, Accelerators and Beams* **4**, 54401 (2001)
4. G.L.Carr, S.L.Kramer, J.B.Murphy, R.P.S.M.Lobo and D.B.Tanner, *Nucl. Instr. & Meth.* **A463**, 387 (2001).
5. M. Abo-Bakr, J. Feikes, K. Holldack, G. Wüstefeld and H.-W. Hübers, to be published.
6. D. X. Wang, G. A. Krafft, and C. K. Sinclair, *Phys. Rev. E*, **57**, 2283 (1998).
7. G.L. Carr, M.C. Martin, W.R. McKinney, K. Jordan, G.R. Neil, and G.P. Williams, to be published.

This work was supported by the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under the Department of Energy Contract No. DE-AC03-76SF00098.

Principal investigator: Michael C. Martin, Advanced Light Source Division, Lawrence Berkeley National Laboratory. Email: MCMartin@lbl.gov. Telephone: 510-495-2231.

Giant Terahertz Power Levels from Relativistic Electrons

G.L. Carr,¹ Michael C. Martin,² Wayne R. McKinney,²
K. Jordan,³ George R. Neil,³ and G.P. Williams³

¹National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973,

²Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720,

³Free Electron Laser, Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606

INTRODUCTION

We present measurements of both power and spectral content that confirm theoretical predictions of the generation of 20 watts (average) of broadband THz radiation pulses. The experiments were performed using the energy recovery linac (ERL) at the Jefferson Lab Free Electron Laser (JLab FEL)[1]. This facility offers a combination of very short electron bunches (~ 500 fs), relatively high average beam current (up to 5 ma), and up to a 75 MHz repetition rate.

The THz region, ($1 \text{ THz} = 33 \text{ cm}^{-1}$ or 4 meV), lies in the far infrared spectral range where conventional thermal sources are very weak. A significant advancement in broadband THz sources has occurred over the past decade with the advent of coherent THz radiation emission from photocarriers in a biased semiconductor[5]. An energy per pulse of about 1 J has been achieved, implying MW peak powers, but at repetition rates of 1 kHz such that average power levels are only 1 mW[5].

The present work describes a different process for producing coherent THz radiation by accelerated electrons. As schematically shown in Figure 1, electrons are photoemitted from GaAs, brought to relativistic energies ($\sim 25 \text{ MeV}$) in a linac and then transversely accelerated by a magnetic field to produce the desired THz emission as synchrotron radiation. If the electron bunch dimensions are small (in particular, the bunch length is less than the wavelength of observation), one obtains a multiparticle coherent enhancement[6,7].

Conceptually it is easy to understand the many orders of magnitude gain realized in these experiments by making a comparison with a more conventional (non-relativistic) THz source. We can compare the power produced per electron, and use Larmor's formula[19] for the radiated power. In CGS units it takes the form:

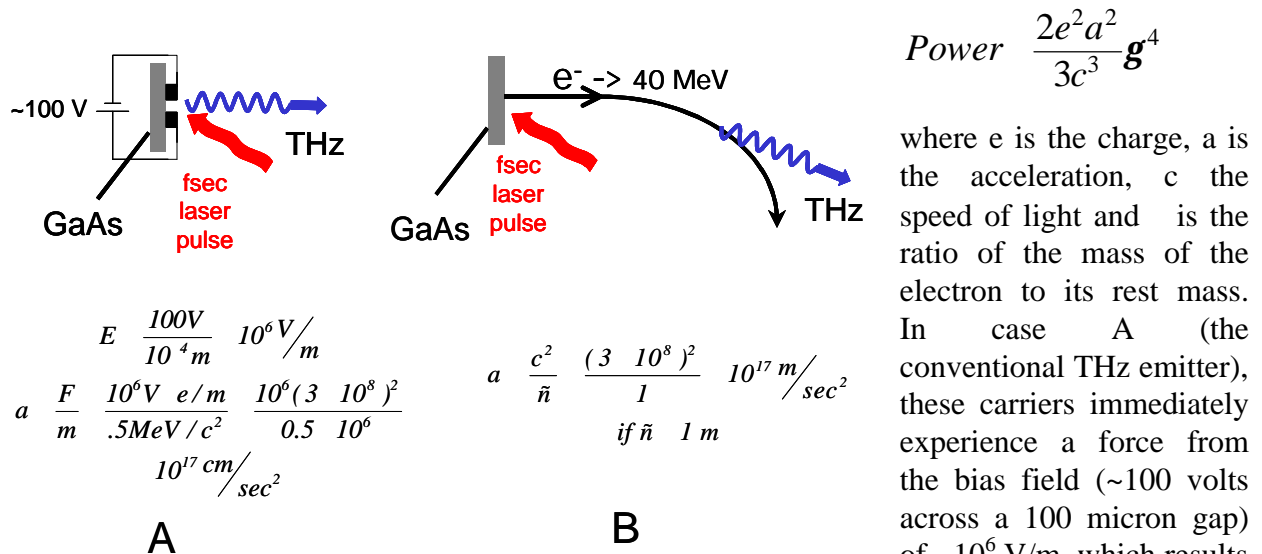


Fig. 1. Comparison between coherent THz radiation generated by a conventional laser-driven THz source (A) and the relativistic source described here (B).

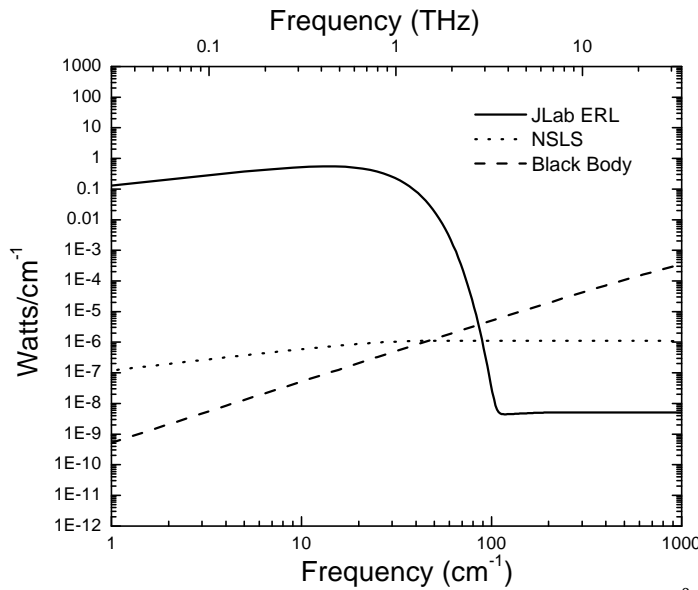


Fig. 2. Calculations of the average power emitted by a 10 mm² 2000 K thermal source (dashed), the NSLS VUV ring at BNL (dotted), and the JLab ERL (solid).

comparable to the bunch length. The resulting spectral content extends up to about 1 THz, the same spectral range as for case A. Thus, assuming the same number of electrons, the ratio of the power radiated by the conventional THz generation to the present generation is given by $\frac{P_{\text{conventional}}}{P_{\text{JLab}}} = 2 \times 10^5$, with $\gamma = 21$. In practice, the electron energy can be significantly larger, but this simply adds relatively weak (incoherent) intensity at higher frequencies and leaves the low frequency (THz) intensity essentially unchanged.

The results of calculations of the radiation for a conventionally synchrotron, a thermal IR source, and the JLab source are shown in Fig. 2 in units of (average) W/cm⁻¹ over the range 1-1,000 cm⁻¹, or 0.03 to 33 THz. The superiority of the JLab ERL in the THz range is clear.

EXPERIMENTAL RESULTS AND DISCUSSION

In our experiments, the electrons were generated using the frequency doubled (530 nm) output of a Coherent Antares model Nd:YLF laser operating at sub-multiples of frequencies up to 74.8 MHz, and with an average power of a few watts incident on a Cs coated GaAs cathode. The resulting photoelectrons were accelerated using a DC voltage of 300 kV into a superconducting linac and accelerated to energies of up to 40 MeV.

The THz radiation was extracted from a dipole magnet of 1 m bending radius immediately prior to the free-electron laser cavity, the latter being unimportant for these experiments. For the total power measurements the light exited the accelerator vacuum chamber through a 10 mm aperture diamond window subtending an angle of 20° × 20 mrad relative to the source point. The emerging beam was focused onto a calibrated pyroelectric detector, with which the total power was measured, and which confirmed the predictions of the calculations for this aperture, charge per bunch and repetition.

The spectral content of the emitted THz light was analyzed using a Nicolet 670 rapid-scan Michelson interferometer with a silicon beamsplitter and a 4.2K Infrared Laboratories bolometer. The diamond window on the accelerator was replaced by a larger crystal quartz window to increase the light collection to 60° × 60 mrad. An 80 cm focal length spherical mirror produced a 48 mm diameter collimated beam compatible with the Nicolet 670 interferometer optics. A

10^{17} m/s². The entire process is completed in less than 1 ps, resulting in spectral content up to a few THz. In case B, the same number of charge carriers are brought to a relativistic energy of > 10 MeV in a linac, after which a magnetic field bends their path into a circle of radius $r = 1$ m resulting in an acceleration $c^2/r = 10^{17}$ m/sec², the same as for case A. An observer for case B also detects a brief pulse of electromagnetic radiation as an electron bunch passes by. The bunch length determines the spectral range over which the coherent enhancement occurs. For an electron energy of 10 MeV ($\gamma = 21$), and with $r = 1$ m, we obtain a dt of about 500 fs, which is

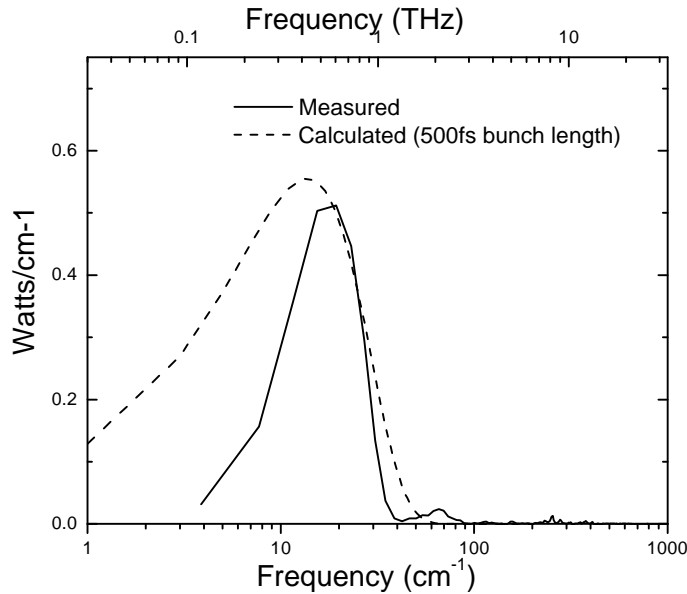


Fig. 3. Comparison between measured (solid line) and calculated (dashed line) THz spectral intensity.

curve for a bunch length of 500 fs in Fig. 3. We have scaled the data to fit the theory on the basis of the absolute power measurements. The spectral onset of the super-radiant enhancement is clearly seen, and the onset shape is also seen to match closely the theoretical predictions. Note that the discrepancy on the lower frequency side is due to diffraction effects.

We have another reference point for determining the absolute power since we were able to switch sources from the THz emission port to a 1300 K thermal source (the spectrometer's standard global source). At a frequency of 12 cm^{-1} we obtained a ratio of intensity from the THz source to that of the global of 2×10^4 . To compare with the calculation, we multiply the THz source results by the reduction factor of 550, as discussed earlier. This implies a measured advantage of the JLab THz source over the global of 10^7 . The calculation predicts an enhancement of $(0.6 / 6 \times 10^{-8}) = 10^7$. While there is apparent agreement, these simple arguments have ignored diffraction and other effects on the detection efficiency of both sources. However, the result does indeed affirm the THz power.

We additionally observed the expected quadratic dependence of the coherent THz intensity on the number of electrons in the bunch, and the intensity ratio for the horizontal to vertical polarization components was measured to be 5. The expected polarization ratio for 30 cm^{-1} and 60 mrad is about 6, so we consider this to be good agreement.

CONCLUSIONS

We have demonstrated that the short bunches which circulate in energy recovery electron circulating rings with sub-picosecond electron bunch lengths yield broadband high brightness THz radiation with close to 1 W/cm^2 of average power into the diffraction limit and peak powers about 10^4 times higher than this.

This work was supported primarily by the U.S. Dept. of Energy under contracts DE-AC02-98CH10886 (Brookhaven National Laboratory), DE-AC03-76SF00098 (Lawrence Berkeley National Laboratory) and DE-AC05-84-ER40150 (Thomas Jefferson National Accelerator Laboratory). The JLab FEL is supported by the Office of Naval Research, the Commonwealth of Virginia and the Laser Processing Consortium.

Principal investigator: Michael C. Martin, Advanced Light Source, Lawrence Berkeley National Laboratory. Email: MCMartin@lbl.gov. Telephone: 510-495-2231.

switching mirror allowed a remote choice of source, namely the THz light from the accelerator, or a $T=1300 \text{ K}$ thermal reference source.

For the spectroscopy experiments, the analysis and detection system did not have sufficient dynamic range to cover the 7 decades in power difference between the 2 sources. We chose to make measurements at 584 kHz, instead of 37.4 MHz, and at a charge per bunch of 34 pC instead of the maximum of 100 pC, thereby reducing the THz power by a factor of $(37 \times 10^6) / (584 \times 10^3) (100/34)^2$, or approximately 550.

We show the results of the measurements along with a calculated